AD-A095 868 MAINE UNIV ORONO DEPT OF PHYSICS F/G 20/4
INVESTIGATION OF BULK TURBULENCE AND NONLINEAR WAVE PHENOMENA I--ETC(U)
SEP 80 J A ROONEY, C W SMITH AFOSR-76-3113

UNCLASSIFIED AFOSR-TR-81-0186 NL

1 OF 1
AD
A095868

END
DATE
FILMED
3 81
DTIC

SECURITY CLASSIFICATION OF THIS PAGE UNCLASSIFIED LEVEL II

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER AFOSR-TR-81-0186	2. GOVT ACCESSION NO. AD-A095 868	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) INVESTIGATION OF BULK TURBULENCE AND NONLINEAR WAVE PHENOMENA IN LIQUID HELIUM		5. TYPE OF REPORT & PERIOD COVERED INTERIM
		6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) James A. Rooney, Charles W. Smith		8. CONTRACT OR GRANT NUMBER(s) AFOSR-76-3113
9. PERFORMING ORGANIZATION NAME AND ADDRESS University of Maine, Department of Physics, Orono, ME 04469		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS 61102F 2301/A5
11. CONTROLLING OFFICE NAME AND ADDRESS AFOSR/NP Bolling AFB, DC 20332		12. REPORT DATE Sep 1980
		13. NUMBER OF PAGES 18
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)		15. SECURITY CLASS. (of this report) unclassified
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

DTIC ELECTE MAR 4 1981 S D

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Liquid Helium
Ultrasonic cavitation
Electron - bubble Statr
Turbulence

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Generation of Turbulence by Ultrasound in HeII.

We have both extended our earlier measurements of the dynamics of turbulence and developed a better model to describe the ultrasonic generation of superfluid turbulence. This analysis of the turbulent superfluid helium provides the first determination of the negative ion-vortex line cross-section and the negative ion occupation length along a vortex line. A paper entitled

DD FORM 1 JAN 73 1473 UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

#20.

"Turbulence Dynamics in Sonated Superfluid Helium" has been written and a preprint is attached.

B. Use of Acousto-optic Techniques to Detect Subharmonic and Cavitation Activity.

Optical systems have been developed to probe liquid helium in the presence of ultrasound. We have established that light scattering is a sensitive technique to detect cavitation. This acousto-optic technique has the advantages that it is noninvasive and can be used to scan through the region of interest. A paper has been published on the subject and a copy is attached.

C. Use of Acousto-optic Techniques to Measure Nonlinear Properties of Cryogenic Liquids.

In addition we have begun to use an acousto-optic technique to measure the nonlinear parameters of cryogenic liquids. Asymmetries that develop in the observed diffraction patterns allow one to determine the nonlinear behavior of the sonated liquids. Raman-Nath theory has been adopted to interpret experimental data.

D. Studies of Acoustic Streaming in Superfluid Helium.

Acoustically produced fluid flow called acoustic streaming has been studied in the normal and superfluid state. Three distinct flow regimes were observed. The flow changes in an orderly manner at the threshold for the onset of vortex production but becomes complex at high acoustic amplitudes. A manuscript on this work is in preparation.

AFOSR-TR- 81-0186

INVESTIGATION OF BULK TURBULENCE AND NONLINEAR WAVE PHENOMENA IN LIQUID HELIUM

AFOSR-76-3113

Maine Univ.

SUMMARY OF RESEARCH FOR GRANT PERIOD 10/1/79 - 9/30/80

In order to place our research in perspective we briefly review previous work on pertinent subjects. Our group was the first to experimentally investigate cryogenic liquids using combined ultrasonic and electron bubble techniques, and the first to investigate ultrasonically generated homogeneous turbulence in liquid helium. Earlier work on cavitation by Neppiras and Finch presented a qualitative description of subharmonic and white noise spectral components as well as determination of the threshold pressure amplitudes for production of these spectral components. In superfluid helium Finch and co-workers have attempted to relate turbulence phenomena to cavitation thresholds. The interaction of ions and turbulence in thermal counterflow tubes has been studied by Ashton and Northby.

Our work to date has centered on four discoveries made in our laboratory. First, we found that ultrasonic transducers in the megahertz frequency range were efficient generators of turbulence, and that we could characterize this turbulence with measurements of electron bubble currents. Second, we found that the first subharmonic of the applied sound field appeared in the liquid simultaneously with the onset of turbulence. Third, we have optically detected the first subharmonic in the bulk liquid and have observed the asymmetry of the propagating sound wave using laser light diffraction. Fourth, we have observed normal fluid streaming at $T < T_\lambda$. The results of these experiments are described briefly in Section A, B, C and D below. We list publications for the period covered by this report in Section E and personnel empolyed in Section F.

A. Generation of Turbulence by Ultrasound in He II.

We immersed in liquid helium a one curie tritium source, a grid and a collector-guard ring combination. Voltages applied to the source and collector select the appropriate charge species (electron bubble or positive ion) from near the source and inject a current into the region between grid and collector. A PZT4 thickness mode transducer resonant at $\omega/2\pi = 1$, 3 or 10 MHz was mounted in the grid-collector region. We then observed the current as the displacement amplitude of vibration of the transducer was increased. We observed: (1) Positive currents are independent of sound amplitude for $1.3K \leq T \leq 2.0K$. (2) Negative currents are strongly attenuated above a threshold displacement amplitude, A_c, for $T \leq 1.80K$. (3) The rapid increase in this attenuation between T = 1.80K and T = 1.60K is strong evidence that the electron bubbles are trapped by quantized vortex lines, as it is known that electron bubble lifetimes on vortex lines increase from less than 1 second at T = 1.80K to approximately 1000 second at T = 1.60K. We conclude from these experiments that ultrasound can generate bulk turbulence and that this turbulence may be probed by the negative ion in liquid helium for $T \leq 1.80K$. Further work on this effect showed that the onset of turbulence required a critical fluid velocity $v_c = \omega A_c$ which was independent for ω for $\omega/2\pi = 1$, 3 and 10 MHz, and was found to be $v_c = 0.15 \pm 0.05$ cm/s.

We have now extended these measurements to the non-equilibrium dynamics of the vortex tangle. Analysis of current changes when the ultrasound is turned on and when it is turned off demonstrated clearly that the Vinen equation for the dynamics of homogeneous superfluid turbulence is valid. This was the first experimental confirmation of this equation outside the usual counterflow geometry for which it was derived and repeatedly tested. Through a least squares fitting routine of the equilibrium currents versus sound amplitude and a modeling of the sound on-off current responses we have established values for the coefficients for the growth and decay terms contained in the Vinen equation. In addition, we have made the first experimental determination of the capture width for electron bubbles on vortex lines and the effective occupation length of an electron bubble on vortex line in turbulent He II. We consider this work a significant contribution to the physics of turbulence in liquid helium.

We have thus successfully quantified our novel technique and demonstrated its usefulness. We can now fully exploit it to provide new information about turbulent liquid helium. One of the advantages of our technique is the added parameter-frequency. We have accumulated, during this funding period, a body of data on the dynamics of vortex tangle growth and decay over a range of frequencies. Analysis of this data is continuing. It should provide new information on the initiation time for vortex line formation and lead to a detailed understanding of the mechanisms for the generation of turbulence by ultrasound. A manuscript discussing this topic has been prepared and a copy is attached.

B. Use of Acousto-optic Techniques to Detect Subharmonic and Cavitation Activity

In much research and many applications of finite amplitude ultrasound it is important to detect and characterize the acoustic response of the sonicated liquid. In particular it is useful to detect the presence of the subharmonic and the threshold for collapse or transient cavitation. A variety of techniques have been developed for this purpose.

In our work, observations were made of the diffraction patterns produced by the acousto-optic effect in superfluid helium and in methanol for both cylindrical and plane wave sound fields. Thresholds for the subharmonic of order 1/2 and transient cavitation were determined by observation of abrupt changes in the diffraction patterns. The onset of the subharmonic produced additional diffracted signals in a stable diffraction pattern while onset of cavitation completely disrupted the diffraction pattern.

We have found that the acousto-optic method has many advantages: it requires a simple experimental arrangement; it does not disturb either the sound field or flow fields in the liquids; it presents information only from the region of the sound field of interest; the data acquisition is very rapid, and the laser beam can be scanned throughout the volume of interest. The results are generally applicable and we have observed similar changes in the diffraction patterns for more usual liquids including water and methanol when sonicated in the megahertz frequency range. In summary, this technique has several distinct advantages with respect to other detection methods and may be useful in a variety of applications.

A paper of the same title describing the technique has been published in Ultrasonics. A copy is attached.

C. Use of Acousto-optic Techniques to Measure Non-linear Properties of Cryogenic Liquids.

In addition we have begun to use an acousto-optic technique to measure the nonlinear parameters of cryogenic liquids. In these studies a laser beam is diffracted by the sound field as described in section B. For low sound amplitudes the diffraction pattern formed is symmetric with respect to zero order diffraction. For higher amplitudes this pattern becomes asymmetric as the propagating waveform becomes distorted because of the nonlinear parameters of the propagation medium. During this grant period we have developed techniques using photodiodes and preamplication to quantify the observed asymmetries. We plan to extend these measurements to examine details of the nonlinear properties of liquid helium during the current grant period.

Development of theory appropriate for analysis of the asymmetries complemented the experimental efforts. The theory is an adaption of the Raman-Nath theory to our specific application. The theory is developed to relate the distortion in the diffraction pattern to available isothermal compressibility measurements. The theory includes the effects of absorption. The theory was successfully tested using data available from the literature.

D. Studies of Acoustic Streaming in Superfluid Helium

We have employed PZT4 ceramic transducers to acoustically produce fluid flow called acoustic streaming in superfluid helium. The sound field propagates between two flat plates inducing mass flow perpendicular to a narrow beam of negative ions. The deflection of the beam is measured by a series of ion current collectors in one of the flat plates. Average streaming velocities v, as low as 0.01 cm/s may be resolved and velocities on the order of 1 cm/s can be observed. Three distinct flow regimes are evident for increasing sound amplitude. At the lowest amplitudes v is propostional to U_o^2, where U_o is the transducer velocity amplitude, as predicted by theories for streaming in normal liquids. Near $U_o \approx 0.3$ cm/s a transition occurs to a new flow regime for which the streaming velocity increases more slowly but is again proportional to U_o^2. The values of v for which this transition occurs decreases sharply with increasing temperature for $1.4K < T < 2.0K$. At still higher sound amplitudes, more complex flows develop. These studies not only provide basic insight into the development and dynamics of turbulence in superfluid helium but are important to design of effective mass and heat transfer systems in superfluid helium. A manuscript on this aspect of the research is in preparation.

E. Publications and Professional Presentations

a. Publications

1. R. F. Carey, J. A. Rooney and C. W. Smith, "Turbulence Dynamics in Sonated Superfluid Helium" submitted to Phys. Rev. Letter (preprints attached)

2. R. F. Carey, J. A. Rooney and C. W. Smith, "Use of Acousto-Optic Techniques to Detect Subharmonic and Cavitation Activity" Ultrasonics (reprint attached). Sept. 213-215 (1980).

3. R. F. Carey, J. A. Rooney and C. W. Smith, "Measurement of Acoustic Streaming Velocities in Superfluid Helium" Bull. Am. Phys. Soc. 25 389 (1980) (reprint attached).

4. R. F. Carey, J. A. Rooney and C. W. Smith "Acoustic Streaming in Superfluid Helium" J. Acoust. Soc. Am. 67 Supl. 1 S56 (1980) (reprint attached).

5. R. F. Carey, J. A. Rooney and C. W. Smith, "Studies of Acoustic Streaming in Liquid Helium" (in preparation).

b. Presentations at Professional Societies

1. "Measurement of Acoustic Streaming Velocities in Superfluid Helium, Spring meeting of the American Physical Society, New York City, March 1980.

2. "Acoustic Streaming in Superfluid Helium, Spring meeting of the Acoustical Society of America, Atlanta, April, 1980.

F. Personnel

1. James A. Rooney, Ph.D.

   Associate Professor of Physics

2. Charles W. Smith, Ph.D.

   Associate Professor of Physics

3. Ronald F. Carey, Ph.D.

   Visiting Research Assistant Professor of Physics

4. Ali Kashkoo , M.S.

   Graduate Student in Physics

11/7/79

Turbulence Dynamics in Sonated Superfluid Helium

R.F. Carey, J.A. Rooney and C.W. Smith
Department of Physics and Astronomy
University of Maine, Orono, Maine 04469

We have used ultrasound to generate turbulence in bulk superfluid helium. Attenuation of negative ion current by the vortex tangle allows a quantitative examination of the turbulent state. Both the steady state and dynamic response of the vortex tangle to changes in ultrasound amplitude are tested. This sonically generated turbulent state is described very well by the Vinen Equation, indicating a qualitative similarity between this new turbulent state and that generated by heat currents.

Measurements of the critical flow velocity for the onset of dissipation in superfluid helium have shown that the lowest energy excitations generated at the critical velocity are vortices with quantized circulation $\kappa = h/m$, where h is Planck's constant and m is the mass of a helium atom. Considerable effort[1-6] has been expended to understand the turbulent state induced by flow rates well above the critical value. The fully developed turbulent state consists of a dense tangle of vortex line in a dynamic equilibrium in which line growth and decay rates are equal.

In a series of four papers, Vinen[1] provided experimental evidence for and a phenomenological description of superfluid turbulence in counterflow tubes. When wall effects may be ignored, his model predicts the rate of change of the vortex line length density, L:

$$\frac{dL}{dt} = \chi_1 \frac{B\rho_n}{2\rho} V_{nL} L^{3/2} - \chi_2 \frac{\kappa}{2\pi} L^2 \qquad (1)$$

where B is a temperature dependent parameter which describes the normal fluid - vortex line interaction as measured by rotation experiments[7], ρ_n/ρ the normal fluid density ratio, V_{nL} the relative velocity between the normal fluid and the vortex line, and χ_1 and χ_2 are dimensionless parameters of order unity. The steady state solution of Eq (1) yields an expression for the steady state vortex line length density, L_o,

$$L_o^{1/2} = \left(\frac{\chi_1}{\chi_2}\right) \left(\frac{\rho_n}{\rho}\right) \left(\frac{\pi B}{\kappa}\right) V_{nL} \tag{2}$$

Childers and Tough[4] have shown that Eq. (2) provides a good description of turbulent flow up to the limit where channel size becomes comparable to $L_o^{-1/2}$, the average interline spacing. Ashton and Northby[5] used an ion technique in thermal counterflow to establish values for (χ_2/σ) and $(\chi_1/\chi_2)^2/\ell$ where σ is the capture width for the negative ion-vortex line interaction and ℓ is the effective occupation length of an ion on a vortex line. The recent detailed calculations by Schwarz[8] show that Eq. (1) is of the correct form by developing a description of the vortex tangle from a microscopic rather than phenomenological point of view.

We describe here experiments which investigate the vortex tangle generated by ultrasound. We show that both Eqs (1) and (2) may be used to describe this vibrationally induced distribution of vorticity. A preliminary description of our steady state results has appeared[9]. The measurements were performed in an open geometry in which inherently anisotropic counterflow is avoided. In the inset of Fig. 1 we show a schematic representation of the experimental cell. A control grid in front of a one curie tritium source is used to inject negative ions into the grid-collector space. An electric field intensity of 50V/cm draws the ions toward the guarded collector. A calibrated three megahertz PZT4 thickness mode transducer is used to sonate the region in the grid-collector space. A standing wave resonance is not present. Below 1.75K the vortex tangle traps a fraction of the available negative ions resulting in a space charge between the source and the collector. This space charge limits the current. The change in current can be related to the vortex line density by an extension of the arguments of Reference 5. The rate at which ions are trapped is determined by the trapping probability $P_t = \sigma\,(L-\ell N)$ times the ion flux j/e. Here N is the number density of trapped charge and $(L-\ell N)$ is the effective length of line per unit volume available for trapping. The ion escape rate, P_e, is determined only by vortex line decay (from Eq. (1)):

$$P_e = \frac{1}{L}\left(\frac{dL}{dt}\right)_{\text{decay}} N = \frac{\chi_2\ \kappa}{2\ \pi}\ L\ N$$

Then

$$\frac{dN}{dt} = \frac{\sigma j}{e}\,(L-\ell N) - \frac{\chi_2\ \kappa L N}{2\pi} \tag{3}$$

The space-charge-induced current density change Δj will be directly proportional to N:

$$\Delta j = (ed^2/2\ \varepsilon_0)\ (dj/dV)\ \ N = (1/K)\ \ N \tag{4}$$

where d is the grid-collector spacing and (dj/dV) is the slope of the sound off j(V) characteristic curve for our experimental cell. The time dependence of Δj is determined by $(d\Delta j/dt) = (1/K)\ dN/dt$, which gives

$$\frac{d\Delta j}{dt} = -\Delta j\ \left[\frac{\sigma L}{eK} + \frac{\sigma j_o \ell}{e} + \frac{\chi_2 \kappa L}{2\pi}\right] + \frac{\sigma j_o L}{eK} + \frac{\sigma(\Delta j)^2\ \ell}{e} \tag{5}$$

where j_o is the equilibrium sound-off current density. Setting $d\Delta j/dt = 0$, the equilibrium sound-on change in current density is

$$\Delta j = 1/2\ (j_o + b_1\ b_2\ V_{nL}{}^2) - \{1/4\ (j_o + b_1\ b_2\ V_{nL}{}^2)^2 - b_2 j_o V_{nL}{}^2\}^{1/2} \tag{6}$$

where

$$b_1 = 1 + \frac{eK\kappa}{2\pi}\ \left(\frac{\chi_2}{\sigma}\right)$$

and

$$b_2 = \left(\frac{\pi \rho_n B}{\rho \kappa K^{1/2}} \right)^2 \frac{(x_1/x_2)^2}{\ell}$$

Due to the passing sound wave each fluid element moves with the local velocity $V_s \approx V_n = \omega\xi_0 \cos \omega t$, when the transducer displacement is given by $\xi = \xi_0 \sin \omega t$. The amount of vorticity generated is dependent upon the vibrational amplitude. Therefore, we expect $V_{nL} \propto \omega\xi_0$. To analyze our data we set $V_{nL} = \omega\xi_0$ in Eqs. (5) and (6). This allows us to evaluate the parameters x_1 and x_2 for sonically generated turbulence and to make comparisons with heat current data. In Fig. 1 we plot ion current versus transducer velocity amplitude at two temperatures. The curves calculated using Eq. (6) agree well with experimental observations. By using b_1 and b_2 as parameters in a least squares fit, values of the ratios x_2/σ and $(x_1/x_2)^2/\ell$ may be extracted from these steady state results. Values for these ratios are given in TABLE 1.

We have measured the current during the growth and decay of the vortex tangle as the ultrasound is abruptly turned on and off for $1.35K < T < 1.75K$ and for 0.5 cm/s $< \omega\xi_0 < 3$ cm/s. To analyze the time response of the vortex tangle we define a delay time, $\tau_{1/2}$, as that interval after an abrupt change of the ultrasound amplitude, $V = \omega\xi_0$, in which the current changes by one half of the total change needed to reach a new equilibrium. Such delay times for the OFF case can be described by the equation $\tau_{1/2} = aV^{-1/2}$ with $a = 19$ sec$^{3/2}$ cm$^{-1/2}$. The ON case delay times range from 5 seconds at 2.5 cm/s to 50 seconds at 0.3 cm/s, and can be described by the equation $\tau_{1/2} = bV^{-1}$, with $b = 14$ sec^2 cm^{-1}. These ranges of delay times and velocities are similar to those observed by Vinen for constrained geometries (using heat current/second sound techniques).

Fig. 2 shows three ON-OFF sequences at T = 1.40K for velocity amplitudes V = 0.76, 1.09 and 1.52 cm/s. The solid smooth curves were calculated by numerically integrating Eq. (5). There is excellent agreement between experimental measurements and the results calculated using Vinen's phenomenological equation. These curves were obtained by holding the ratios $(\chi_1/\chi_2)^2/\ell$ and χ_2/σ fixed at the values determined by the steady state solution and varying the values of the individual parameters for a best fit to the data. The values of the parameters determined by this procedure for the data of Fig. 2 are listed in TABLE I. It should be emphasized that, in order to satisfy the conditions imposed by the steady state solution simultaneously with the ON and OFF profiles, the individual parameters are strongly constrained. Variations as small as 5% in any single parameter are noticeable in the quality of the fit. The values presented here for the capture width σ (0.2 - 0.5 μm) and for the occupation length ℓ ($\approx$8 μm) are the first experimentally determined for the case of a vortex tangle. The capture width for vortex line within the tangle is observed to be of the same order of magnitude as that found for a parallel array of vortex lines at the same electric field intensity[10]. The values obtained for the occupation length are 25 times larger than the minimum length, ℓ_{min}, estimated from the negative ion/vortex line binding energy at the temperature and electric field intensity used: $kq^2/\ell_{min} \approx E_b$, which gives $\ell_{min} \approx 0.3$ μm.

As seen in TABLE I our measurements of $(\chi_1/\chi_2)^2/\ell$ and χ_2/σ are similar to those obtained by Ashton and Northby by their ion probe/channel flow technique. Resolution of the ratios into individual parameters using our data and the dynamical equation allows us to compare values of χ_1/χ_2 and χ_2 with those obtained by Vinen. We find similar values for (χ_1/χ_2) although we observe a stronger temperature dependence than either Vinen[1] or Ladner and Tough[6]. Values for χ_2 are somewhat smaller than those observed in counterflow tubes. However the general agreement indicates a strong similarity in the

character of the vortex tangles generated and probed by different techniques in different geometries. It should be noted that a significant detail of Vinen's results is replicated in these experiments. There appears to be consistent factor of five between the values of χ_2 determined during vortex tangle growth as compared to that determined during decay. This factor was clearly demonstrated in Vinen's work and it was necessary in our work to include this factor in order to obtain the fits of Eq. (5).
It is clear that this detail must be addressed in future experiments of this type, as well as in theoretical descriptions of the dynamics of the vortex tangle.

It might be argued that the collapse of cavitation bubbles are the appropriate generating mechanism for vortex lines in the sound field. In fact, it has been shown[11] that the first subharmonic, long considered a precursor of cavitation in liquids, is present in superfluid helium for sound amplitudes in the range where ion trapping on vortex lines takes place. However, the sound amplitude required for visible cavitation is two orders of magnitude greater than that used here. In addition, the measured frequency dependence of threshold and the threshold amplitudes for subharmonic generation are not in agreement with a bubble model[12]. We feel that other nonlinearities in the fluid response to the sound field are responsible for subharmonic generation and may also be responsible for vortex generation. We are presently evaluating the shape of the waveform via light diffraction and the effects of acoustic streaming in order to better understand the mechanism involved.

We conclude that from the quality of the theoretical fit to the data, the reasonable values of the system parameters and the rigidity by which these parameters are constrained by the equation, that these results represent a description of a new distribution of vorticity in superfluid helium which is qualitatively similar to that generated by heat currents. The ultrasonic technique holds two distinct advantages: it may be possible to generate isotropic turbulence with ultrasound, and an additional experimental parameter, the frequency of the ultrasound, is available with which to study turbulence generation. Studies of the frequency dependence are underway.

The authors wish to acknowledge the assistance of Mr. David E. Clark during the data acquisition phase of this study. This work was supported in part by a grant from the United States Air Force Office of Scientific Research.

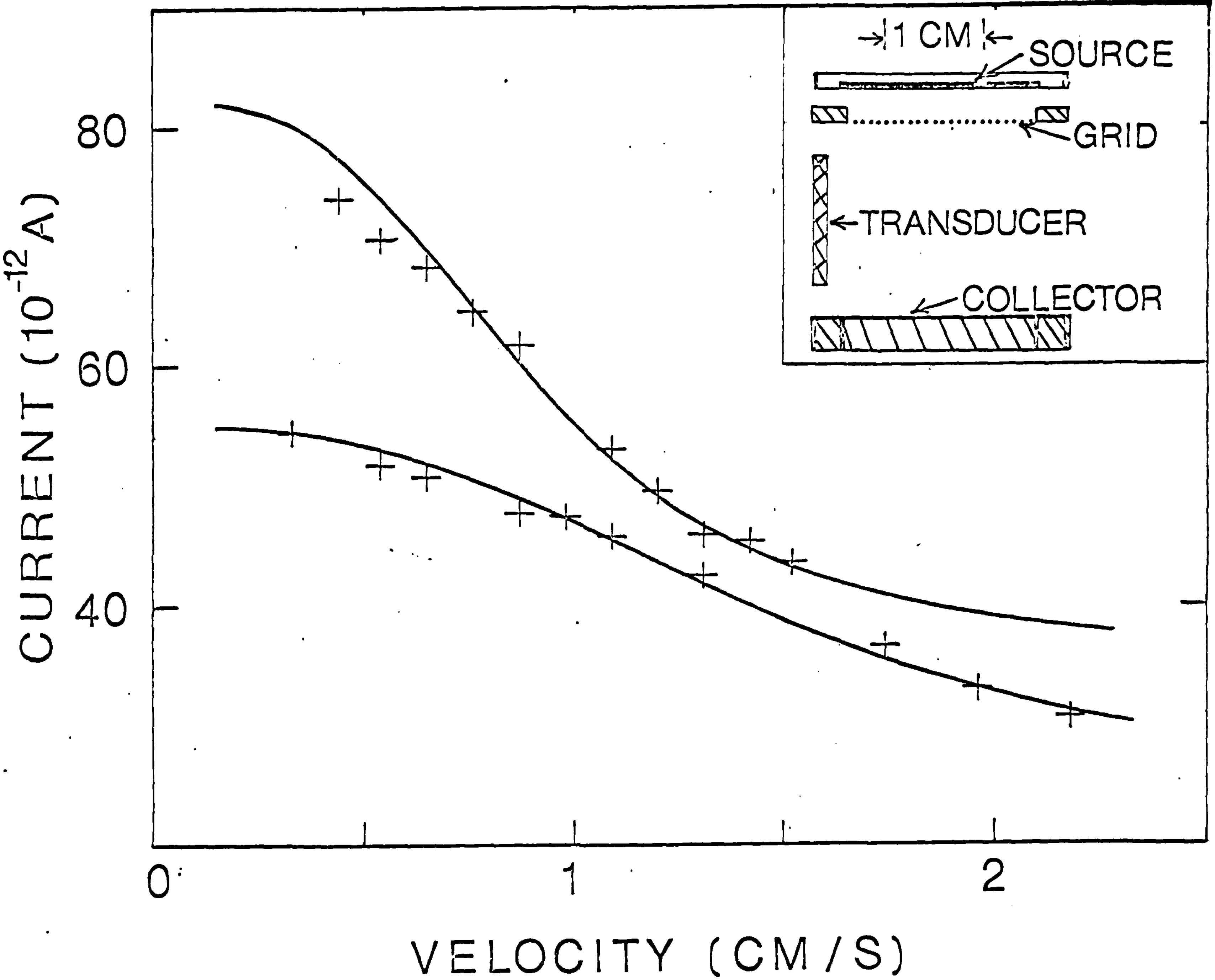
References

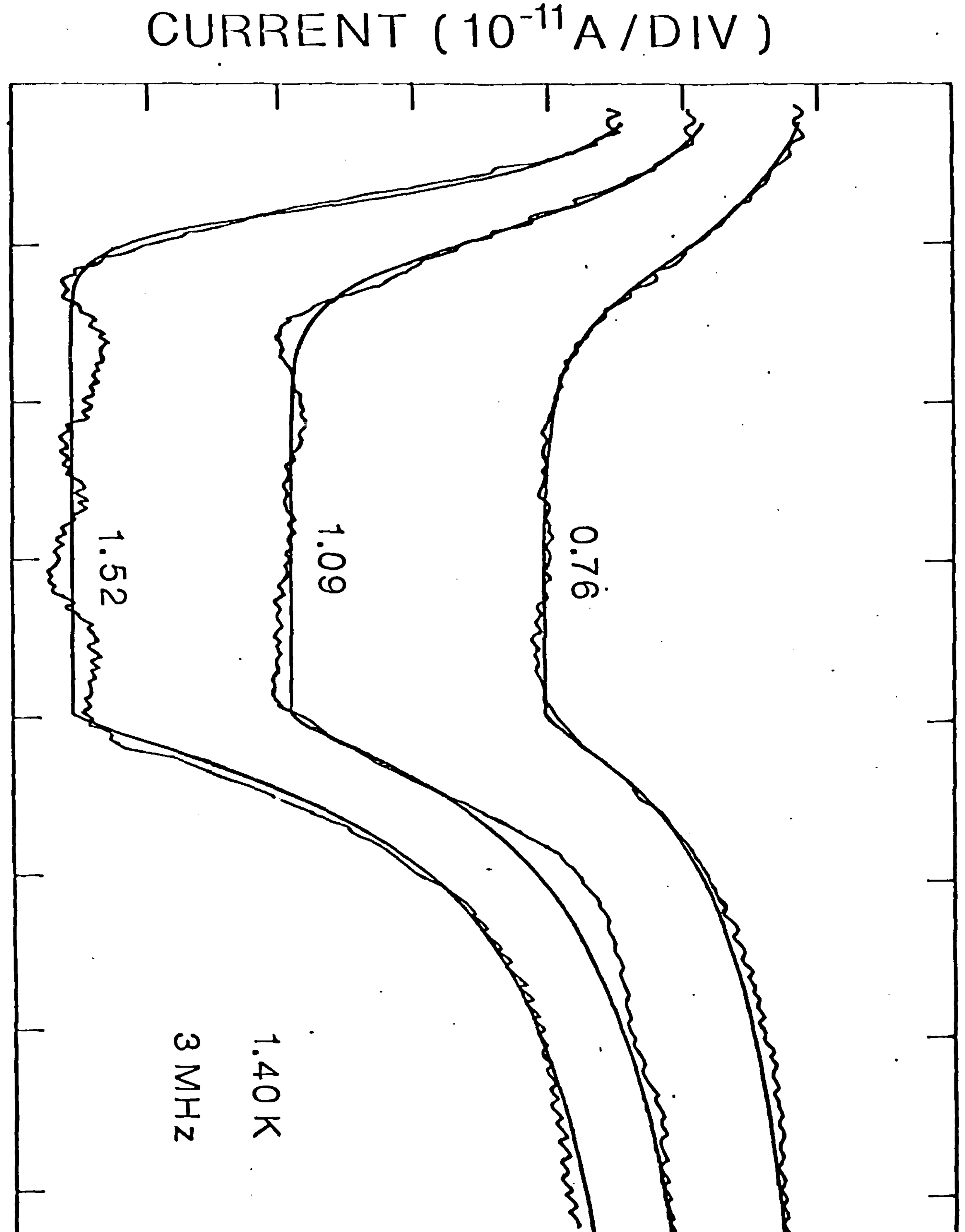
1. W.F. Vinen, Proc. R. Soc. A 240, 114, 128 (1957); 242, 493 (1957); 243, 400 (1958).
2. C.J. Gorter and J.H. Mellink, Physica 15, 127 (1949).
3. D.F. Brewer and D.O. Edwards, Phil. Mag. 7, 721 (1962).
4. R.K. Childers and J.T. Tough, Phys. Rev. B13, 1040 (1976).
5. R.A. Ashton and J.A. Northby, Phys. Rev. Lett. 30, 1119 (1973).
6. D.R. Ladner and J.T. Tough, Phys. Rev. B20, (1979).
7. H.E. Hall and W.F. Vinen, Proc. R. Soc. A238, 204 (1956).
8. K.W. Schwarz, Phys. Rev. B18, 245 (1978).
9. R.F. Carey, J.A. Rooney, and C.W. Smith, J. de Physique 39, C6-176 (1978).
10. D.J. Tanner, Phys. Rev. 152, 121 (1966).
11. R.F. Carey, J.A. Rooney, and C.W. Smith, Phys. Lett. 65A, 311 (1978).
12. R.F. Carey, J.A. Rooney, and C.W. Smith, J. Acoust. Soc. Am. 66 , (1979).

Figure Captions

Figure 1. Collector current in picoamperes versus transducer velocity amplitude in centimeters/second for two temperatures. The solid lines through the data are least squares fits of Eq. (6). The inset shows a schematic diagram of the experimental cell.

Figure 2. Experimental ON-OFF profiles at three transducer velocity amplitudes (0.76, 1.09 and 1.52 centimeters/second). The solid lines through the data are best fit numerical integrations of Eq. (5).


CURRENT (10^{-12}A)
80
60
40
0
1
2
VELOCITY (CM/S)
1 CM
SOURCE
GRID
TRANSDUCER
COLLECTOR



CURRENT (10^{-11} A / DIV)
1.52
1.09
0.76
1.40 K
3 MHz

TABLE I. Parameters determined from data such as shown in Fig. 1 and 3. Also shown are representative values obtained by Ashton and Northby (Ref. 5) and by Vinen (Ref. 1).

	T (K)	$(x_1/x_2)^2/\ell$ (cm^{-1})	(x_2/σ) (10^3 cm^{-1})	(x_1/x_2)	x_2	σ (10^{-6}cm)	ℓ (10^{-4} cm)	"OFF"[a] Factor
This work	1.40	290	8.1	.51	.14	17	9.1	5.0
	1.53	64	6.8	.24	.14	18	8.8	4.0
	1.60	21	7.9	.13	.22	27	8.2	4.3
	1.70	5.4	9.5	.064	.45	47	7.6	5.5
Ashton & Northby	1.58	19	69[b]	-	-	15[c]	40[d]	-
Vinen	1.60	-	-	.28	1.06	-	-	4.6

a) Divide x_2 and σ by this factor to obtain their respective values during the OFF experiment.

b) Ashton and Northby used a higher electric field strength (140 V/cm). The capture width is strongly dependent upon electric field strength.

c) Estimate based upon Vinen's values of x_2.

d) Estimate based upon Vinen's values of (x_1/x_2).

Use of acousto-optic techniques to detect subharmonic and cavitation activity

R.F. CAREY, J.A. ROONEY and C.W. SMITH

Observations were made of the diffraction patterns produced by the acousto-optic effect in superfluid helium and in methanol for both cylindrical and plane wave sound fields. Thresholds for the subharmonic of order ½ and transient cavitation were determined by observation of abrupt changes in the diffraction patterns. The onset of the subharmonic produced additional diffracted signals in a stable diffraction pattern while onset of cavitation completely disrupted the diffraction pattern.

Introduction

In much research and many applications of finite amplitude ultrasound it is important to detect and characterize the acoustic response of the sonicated liquid. In particular it is useful to detect the presence of the subharmonic and the threshold for collapse or transient cavitation. The variety of techniques developed to accomplish this have been reviewed by Flynn[1] and by Neppiras[2].

The standard technique for the detection of the subharmonic signal has been the use of a hydrophone suspended in the sonicated liquid. This technique has been widely used to characterize the subharmonic signal in both normal[3-5] and cryogenic liquids[6-9]. The rapid increase in the subharmonic of order one-half, that is, at one-half of the driving frequency, has been widely and successfully used as an indicator for the threshold for transient cavitation in normal liquids[5]. However, Neppiras[3] has shown that a low level subharmonic signal can be present at amplitudes below that threshold if bubbles of the proper size are present in the sound field. Such signal levels must be ignored when making cavitation threshold measurements. In contrast, in sonicated superfluid helium the subharmonic can be detected by hydrophones (heliophones) at acoustic amplitudes that are an order of magnitude below the threshold for visible bubble activity and two orders of magnitude below the threshold for collapse cavitation[6-9]. In this liquid the subharmonic signal is associated with the presence of turbulence and may not be related to bubble activity[8,9].

While the sudden increase in the magnitude of the subharmonic signal is one possible operational definition for the threshold of collapse cavitation in normal liquids, a variety of others have also been suggested. Neppiras[2] has categorized these in this way:

The authors are with the Physics Department, University of Maine, Orono, Maine 04469, USA. Paper received 4 February 1980. Revised 11 March 1980.

I. Statistical methods to characterize radial bubble velocities or the energy of the cavitation field

II. Methods for measuring the undissolved gas content of the sonicated liquid.

III. Methods for measuring primary effects of cavitation.

Category I includes measurement of the energy absorbed from the sound field and use of various acoustic spectral components such as white noise to characterize the cavitation activity. These techniques are not specific to any given effect. Category II includes direct measurement of the total volume change in the liquid[10], effect of the undissolved gas on the electrical impedance of the acoustic source,[11,12] its effect on electrical conductivity and acoustic attenuation[13], and its effect on the transparency of the liquid[11,12]. A problem with these techniques has been that they cannot usually distinguish between acoustically active and non-active or 'dead' gas bubbles. Category III includes measurement of sonoluminescence, sonochemical effects, erosive effects and degradation of biological systems, all of which relate to direct effects of cavitation on the particular test system.

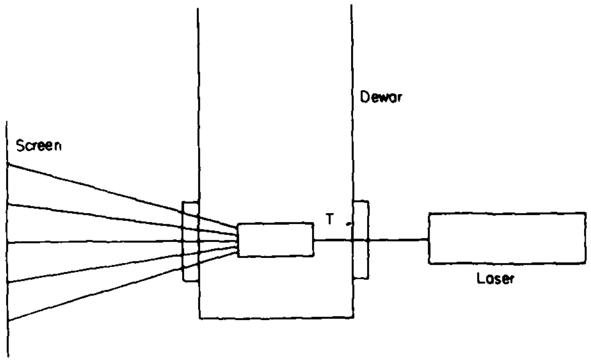


Fig. 1 Schematic drawing of experimental set-up for observing the acousto-optic effect for a laser beam passing along the axis of a cylindrical transducer (T)

 0041-624X/80/050213-03/$02.00

For any application each technique must be rated according to its sensitivity, ease of use and time needed for data acquisition.

In the present paper we describe acousto-optic techniques which fall into category II of the classification of cavitation detection techniques and which are useful both for detection of the subharmonic of order one-half and the threshold for transient cavitation. We have found that the acousto-optic method has many advantages: it requires a simple experimental arrangement; it does not disturb either the sound field or flow fields in the liquids; it presents information only from the region of the sound field of interest; the data acquisition is very rapid, and the laser beam can be scanned throughout the volume of interest.

Methods and results

Many investigators have studied the diffraction of light from the density variations produced by the sound field in a liquid, and these have been reviewed by Damon et al[14]. Light diffraction has been used to measure the intensity of the sound[15] and to determine the non-linear parameters of liquids[16]. Adler and Breazeale[17] have shown that the subharmonic can be detected in normal liquids. However, no one has used the technique to measure the cavitation threshold or subharmonic activity in cryogenic liquids.

We have used two different transducer configurations in our studies. The first is shown schematically in Fig. 1. The beam from a helium-neon laser passed through the optical windows of a Dewar system and through the sound field within a cylindrical 2.6 MHz PZT4 transducer. The sound field produced a diffraction grating within the cylinder. The diffracted laser light passed through the second set of optical windows on to a screen, where it was observed and recorded photographically. Results obtained using this configuration to detect the subharmonic in superfluid helium are shown in Fig. 2. The diffraction pattern below the threshold for the subharmonic is shown in Fig. 2a. It consisted of a series of uniformly spaced concentric rings of varying brightness which represent the various orders of the diffraction pattern. The spacing of the rings depends upon the frequency of the transducer and the distance between the transducer and the viewing screen such that the spacing increases as the frequency is increased or the screen is moved further from the interaction region. The change in this diffraction pattern that occurred when the threshold for the subharmonic of order one-half is exceeded is shown in Fig. 2b. There one notes the presence of an additional set of concentric light rings associated with the subharmonic which are in positions half way between those of the fundamental.

The second configuration is similar to the first but used a plane wave field. The laser beam passed through the optical windows of the Dewar and through the region of a standing plane wave. The resulting diffraction pattern was again displayed and analysed on a screen placed near the exit part of the Dewar. The sequence of diffraction patterns resulting from the interaction of the laser beam in superfluid helium is shown in Fig.3 a-c for three different sound amplitudes. The pattern shown in Fig. 3a is for a low amplitude 3 MHz wave and can be compared with that for the cylindrical field shown in Fig. 2a.

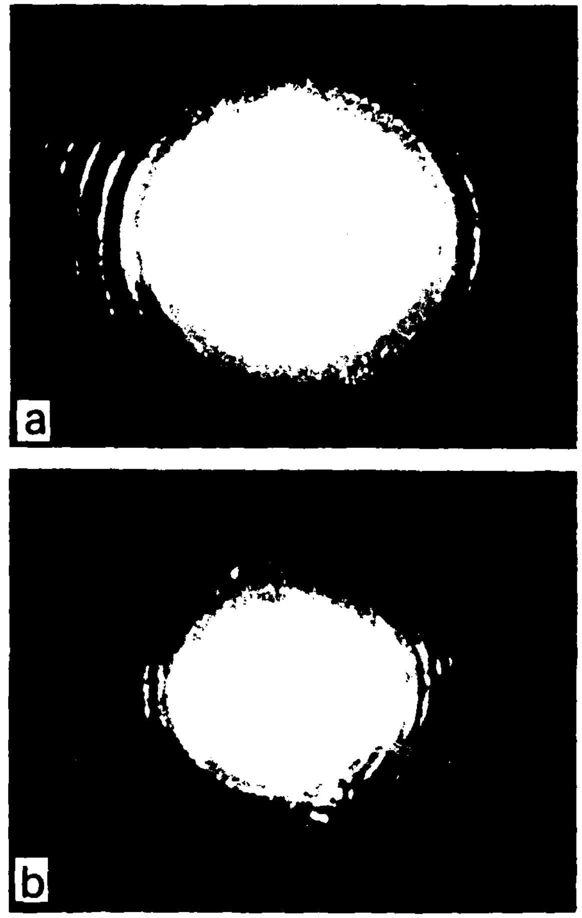


Fig. 2: a – Diffraction pattern produced by the fundamental of a 2.6 MHz cylindrical transducer in superfluid helium at 2.06K; b – diffraction pattern in same experiment for a transducer velocity amplitude of 0.5 cm s^{-1} which is above the threshold for production of the subharmonics of order one-half

We note that the pattern consists principally of a series of spots for the plane wave field, in contrast to the rings of the cylindrical field. In addition a ring of first-order diffraction spots is typically present in our display. The diffraction pattern for sound amplitudes above the threshold for the subharmonic is shown in Fig. 3b. As in the cylindrical geometry, we note the presence of additional diffracted spots at positions half way between those for the fundamental. The observed diffraction pattern was stable with increasing sound amplitude until the threshold for cavitation was exceeded. Then, the diffraction pattern is totally disrupted, as shown in Fig. 3c. This disruption of the pattern was coincident with the onset of a white noise signal in our hydrophone system and was probably the result of the scattering of light from many invisible but sonically active bubbles present above the threshold for cavitation.

We have previously reported subharmonic threshold measurements using a hydrophone and spectrum analyser[8,9] which can determine the threshold to within ±5%. Simultaneous measurements with the acousto-optic technique exemplified in Figs 2 and 3 fix the threshold at only ±20%, but do so non-invasively, simply, and cheaply. The cavitation threshold measurement by disruption of the diffraction pattern was at least as sensitive as other acoustic techniques. We found that the transition from a stable diffraction pattern to

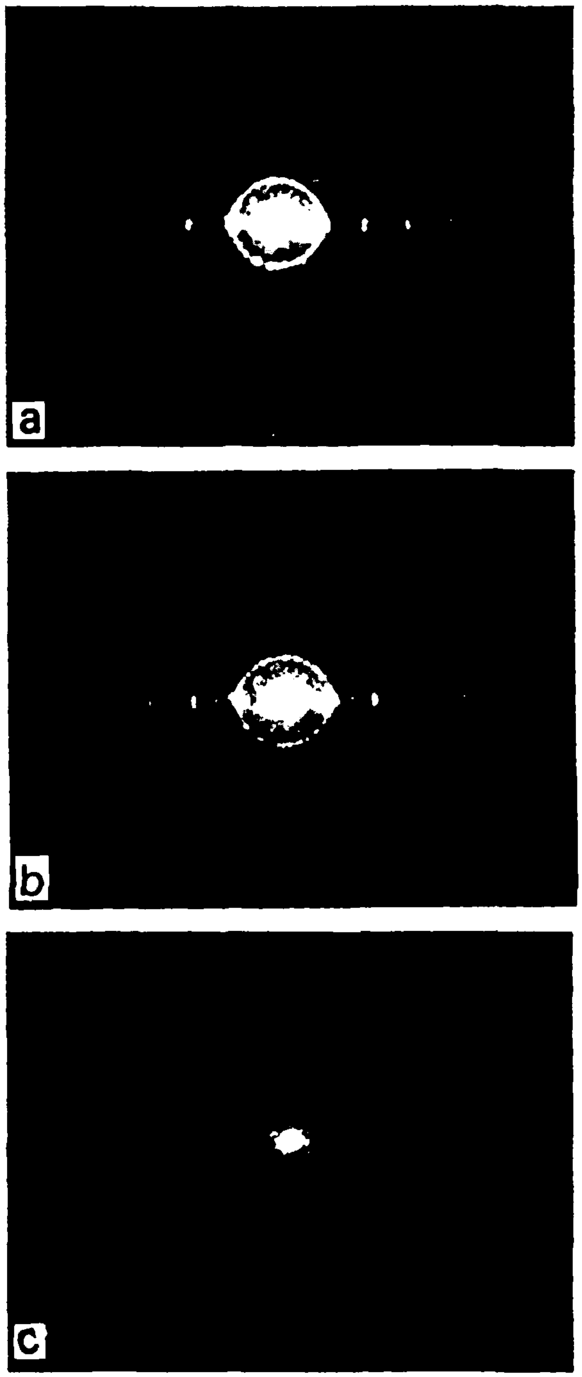


Fig. 3 a Diffraction pattern produced by the fundamental of a 3 MHz plane wave sound field in superfluid helium at 2.06 K; b diffraction pattern for same experimental set-up for amplitudes above the threshold for production of the subharmonic; c - diffraction pattern produced for amplitudes above the threshold for transient cavitation

one of total disruption occurs over a range of less than 1 dB of sound amplitude.

Thus, observations of the diffraction patterns produced by the acousto-optic effect have been used to measure the thresholds for both the subharmonic and cavitation in superfluid helium. The results shown in the figures are for superfluid helium, which is an unusual liquid in that the threshold amplitudes for subharmonic production and cavitation are greatly different. This fact allowed us easily to obtain the results shown because of the stability of the patterns over a large range of amplitudes. However, we have found the results to be more generally applicable and have observed similar changes in the diffraction patterns for more usual liquids including water and methanol when sonicated in the MHz range. In summary, this technique has several distinct advantages with respect to other detection methods, and may be useful in a variety of applications.

Acknowledgement

This work was sponsored in part by the United States Air Force Office of Scientific Research.

References

1 **Flynn, H.G.**, Physics of Acoustic Cavitation in Liquids, in Physical Acoustics, vol 1B, W.P. Mason, Ed. New York, Academic Press, (1964)

2 **Neppiras, E.A.**, Measurement of Acoustic Cavitation, IEEE Trans. Sonics and Ultrasonics, SU-15, (1968) 81

3 **Neppiras, E.A.**, Subharmonic and Other Low-Frequency Emission from Bubbles in Sound-irradiated Liquids, *J. Acoust. Soc. Am.* **45**, (1969) 587

4 **Neppiras, E.A., Coakley, W.T.**, Acoustic Cavitation in a Focused Field in Water at 1 MHz, *J. Sound Vib.* **45**, (1976) 341

5 **Vaughan, P.W.**, Investigation of Acoustic Cavitation Thresholds by Observation of the First Subharmonic, *J. Sound Vib.* **7**, (1968) 236

6 **Neppiras, E.A., Finch, R.D.**, Acoustic Cavitation in Helium, Nitrogen and Water at 10 kHz, *J. Acoust. Soc. Am.* **52** (1972) 335

7 **Mosse, A., Finch, R.D.**, Spectral Analysis of Cavitation Noise in Cryogenic Liquids, *J. Acoust. Soc. Am.* **49** (1971) 156

8 **Carey, R.F., Rooney, J.A., Smith, C.W.**, Subharmonic Responses in Liquid Helium, *J. Acoust. Soc. Am.* **66** (1979) 1801

9 **Carey, R.F., Rooney, J.A., Smith, C.W.**, Ultrasonically Generated Quantized Vorticity in HeII, *Phys. Lett.* **A65** (1978) 311

10 **Mikhailov, I.G., Shutilov, V.A.**, A Simple Method for Observing Cavitation in Liquids, *Sov. Phys. -Acoust.* **5** (1960) 385

11 **Neppiras, E.A.**, Measurements in Liquids at Medium and High Ultrasonic Intensities, *Ultrasonics* **3** (1965) 9

12 **Neppiras, E.A.**, Problems in the Technology of Ultrasonic Cleaning, *Sov. Phys. -Acoust.* **8** (1962) 4

13 **Strasberg, M.** Onset of Ultrasonic Cavitation in Tap Water, *J. Acoust. Soc. Am.* **31** (1959) 163

14 **Damon, R.W., Maloney, W.T., McMahon, D.H.**, Interaction of Light With Ultrasound Phenomena and Applications, W.P. Mason, Ed. Physical Acoustics Vol. 7, Academic Press, NY (1970) 273

15 **Cook, B.D.**, Measurement from the Optical Nearfield of an Ultrasonically Produced Phase Grating, *J. Acoust. Soc. Am.* **60** (1976) 95

16 **Zankel, K.L., Hiedemann, E.A.**, Diffraction of Light by Ultrasonic Waves Progressing with Finite but Moderate Amplitudes in Liquids, *J. Acoust. Soc. Am.* **31** (1959) 44

17 **Adler, L., Breazeale, M.A.**, Excitation of Fractional Harmonic Ultrasonic Waves, Seventh Int. Cong. on Acoustics, Budapest, (1971) 193

The effect of ultrasound on diffusion through membranes

I. LENART and D. AUSLÄNDER

The effect of ultrasound and its mechanisms have been studied in the case of diffusion of electrolytes through cellophane membranes as a function of the intensity of the ultrasonic field, the concentration gradient and the irradiation time.

The main cause of acceleration of diffusion with ultrasound is the appearance of acoustic microcurrents. Also taking part are: radiation pressure, gravitation, cavitation and acoustic pressure.

Values of the diffusion coefficients were calculated from Fick's first law for the case of the stationary processes.

Introduction

The study of the phenomenon of diffusion and its enhancement by ultrasound is of interest owing to its implications in a series of practically important processes including those connected with the field of biology.

The effect of ultrasound and its mechanisms were studied in the case of diffusion through cellophane membranes, for sodium, potassium and calcium chlorides, as a function of the intensity of the ultrasonic field, the concentration gradient and the irradiation time, under thermostated conditions. The modifications of the diffusion flow were studied in ultrasonic fields from 1.2 - 6 W cm^{-2} intensity, at 1 MHz frequency for time intervals from 5 to 30 min at 20°C.

To establish the mechanisms involved, we set up experimental conditions concerning the geometry of the ultrasonic field, which was against the direction and the sense of the diffusion flow and of the gravitational field.

The amounts diffused through the membrane in and outside the field were determined by flame-photometric and conductometric methods.

Experimental results and discussions

The results obtained for KCl (Fig. 1) demonstrate the intensification of the diffusion process by the ultrasonic field. Two groups of curves are shown, corresponding to 0.5 M and 1 M concentration solutions, from which the diffusion was produced, and in each group the effect of ultrasound on the amount diffused is readily apparent. One may notice that the increase in the amount diffused during a given period of time is different, depending on the concentration of the solution and on the ultrasound intensity.

The authors are at the Ultrasonic Laboratory, Babes-Bolyai University, Cluj-Napoca, Romania. Paper received 15 May 1979. Revised 11 March 1980.

The effect of ultrasound depends on the diffusion direction, being greater when the ultrasonic wave is normal to the membrane with the same direction of propagation as the diffusion flow (Fig. 2, curve A). The effect is minimal when the directions of the diffusion flow and of the ultrasonic beam are opposite (curve C). The intermediate curve (B) corresponds to horizontal diffusion, with the field acting parallel to the membrane.

We believe that this effect, that is, the increase in the amount diffused in the ultrasonic field, is mainly due to acoustic microcurrents which increase the velocity of the particles of the medium. The intensity of ultrasound in the field is not

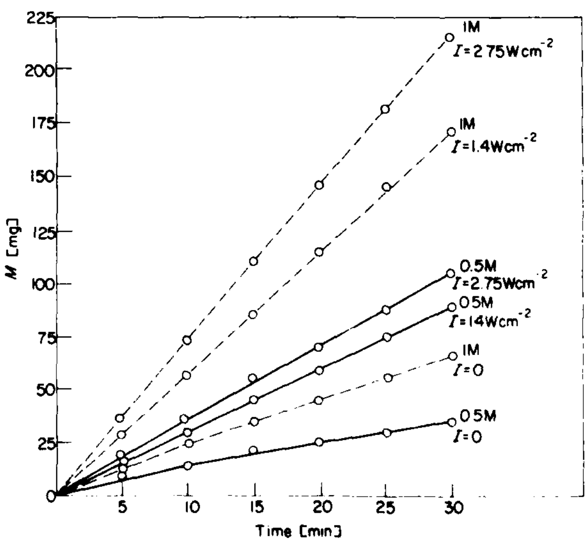


Fig. 1 Variation of the amount of material diffused as a function of time

 0041-624X/80/050216-03/$02.00

Measurement of Acoustic Streaming Velocities in Superfluid Helium. R.F. CAREY, J.A. ROONEY, and C.W. SMITH, University of Maine at Orono* -- We have employed PZT4 ceramic transducers to produce acoustic streaming in superfluid helium. The sound field propagates between two flat plates inducing mass flow perpendicular to a narrow beam of negative ions. The deflection of the beam is measured by a series of ion current collectors in one of the flat plates. Averaged streaming velocities, $\overline{V}_{str}$ as low as 0.01 cm/s may be resolved and velocities on the order of 1 cm/s can be observed. Three distinct flow regimes are evident for increasing sound amplitude. At lowest amplitudes $\overline{V}_{str}$ is proportional to U_o^2, where U_o is the transducer velocity amplitude, as predicted by theories for streaming in normal liquids. Near $U_o \simeq 0.3$ cm/s a transition occurs to a new flow regime for which $\overline{V}_{str}$ increases more slowly but is again proportional to U_o^2. The values of $\overline{V}_{str}$ for which this transition occurs decreases sharply with increasing temperature for 1.4K < T < 2.0K. At still higher sound amplitudes, more complex flows develop.

*Supported in part by a grant from the Air Force Office of Scientific Research

Bull. Am. Phys. Soc. 25 389 (1980).

X3. Acoustic streaming in superfluid helium. **R. F. Carey, J. A. Rooney, and C. W. Smith** (Department of Physics, University of Maine, Orono, ME 04469)

Evidence for the existence of acoustic streaming in superfluid helium has been obtained using a quartz wind transducer configuration operating at 3 MHz. The detection of the streaming and determination of its velocity were made by measuring the deflection of a collimated ion current in liquid helium. The PZT-4 transducer was mounted parallel to the axis of the ion beam and displaced from it. Measurement of the distribution of current along a linear array of small collectors as a function of sound amplitude permitted determination of the streaming velocity. At low amplitudes the streaming velocity increased with the square of the amplitude as predicted by the classical theory for the quartz wind. Above the threshold amplitude for turbulence the streaming velocity increased more slowly but still depended on the square of the amplitude. Evaluation of the rates of increase of the streaming velocity showed that the effective viscosity of the helium was larger by a factor of five above the threshold for turbulence. [This work was supported in part by the Air Force Office of Scientific Research.]

J. Acoust. Soc. Am. 67 Suppl. 1 S56 (1980).

DA

FIL

3 –